Embedded System Design

Stephen A. Edwards

Columbia University

Spring 2019

# Spot the Computer
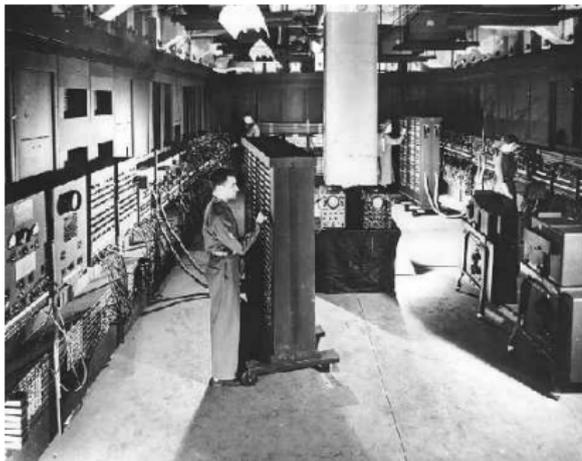
Cars These Days...
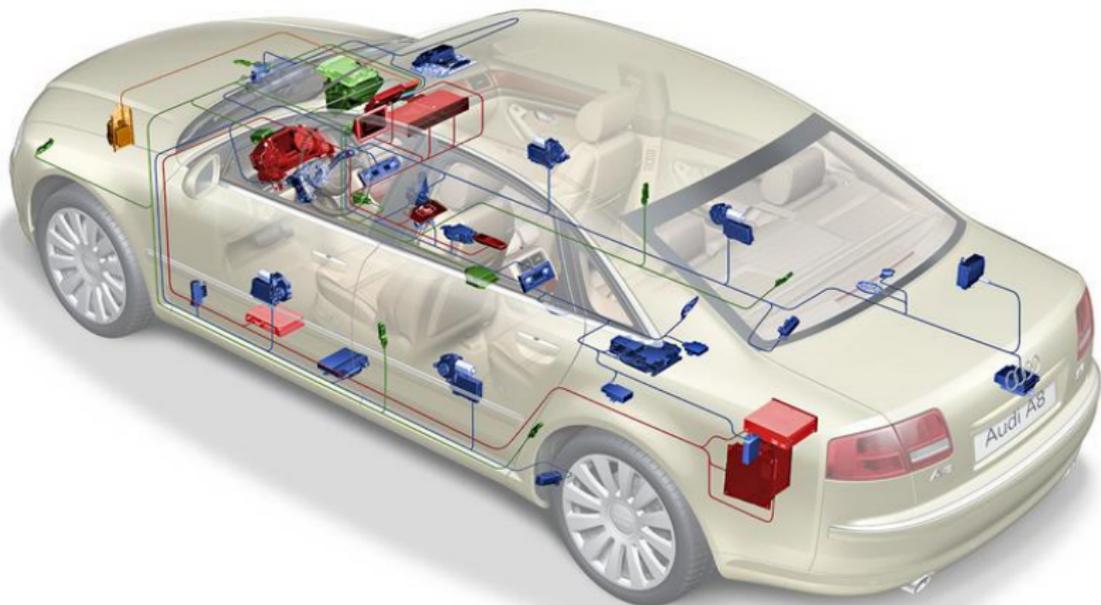
Embedded Systems: Ubiquitous Computers

iPhone

Laser Keyboard

Nikon D300

Video Watch

GPS

Playstation 3

PC Keyboard

SD Card

Inside a Digital Camera
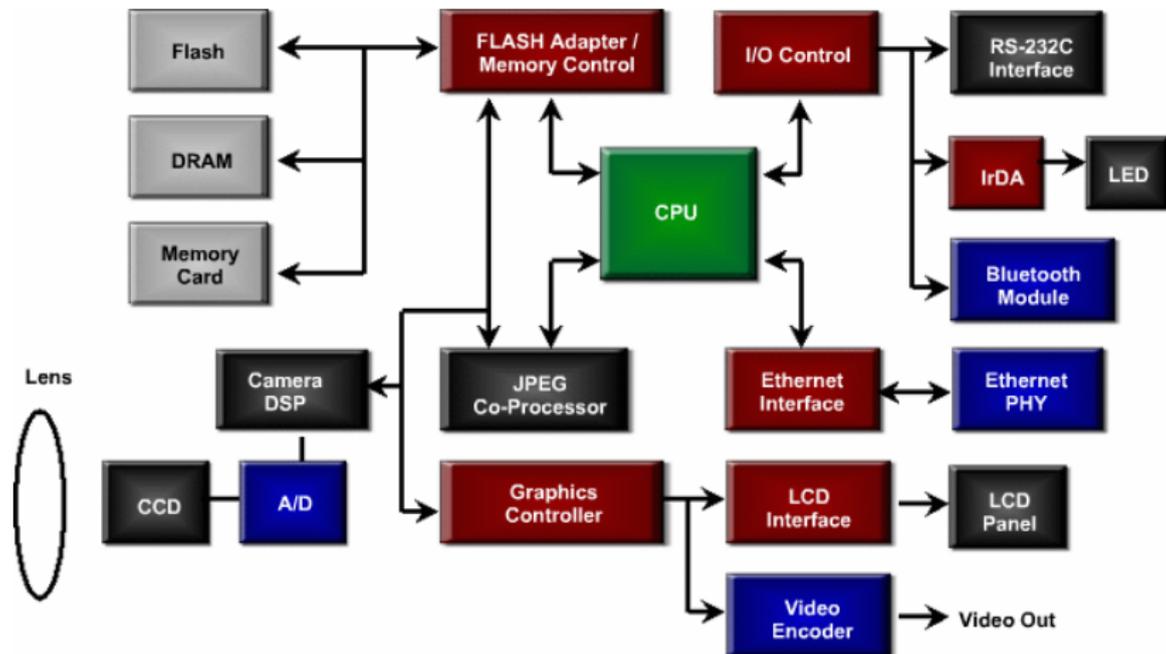
Want an Optimal Device that Meets Constraints On

Price

Functionality

Performance

Size

Power

Time-to-market

Maintainability

Safety

Embedded System Technologies
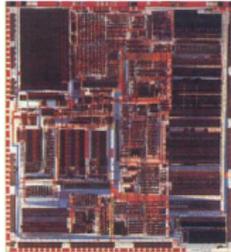
Integrated Circuits

Processing elements

Design tools

IC Technology

1947: First transistor (Shockley, Bell Labs)


1958: First integrated circuit (Kilby, TI)
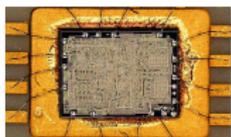
1971: First microprocessor (4004: Intel)
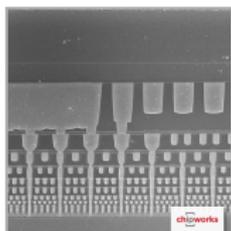
2015: 14 nm features, 13 layers (Intel, Broadwell)

Moore's Law: Transistors per chip

"The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase."

— Gordon Moore, 1965

≈ 1.5 × /year
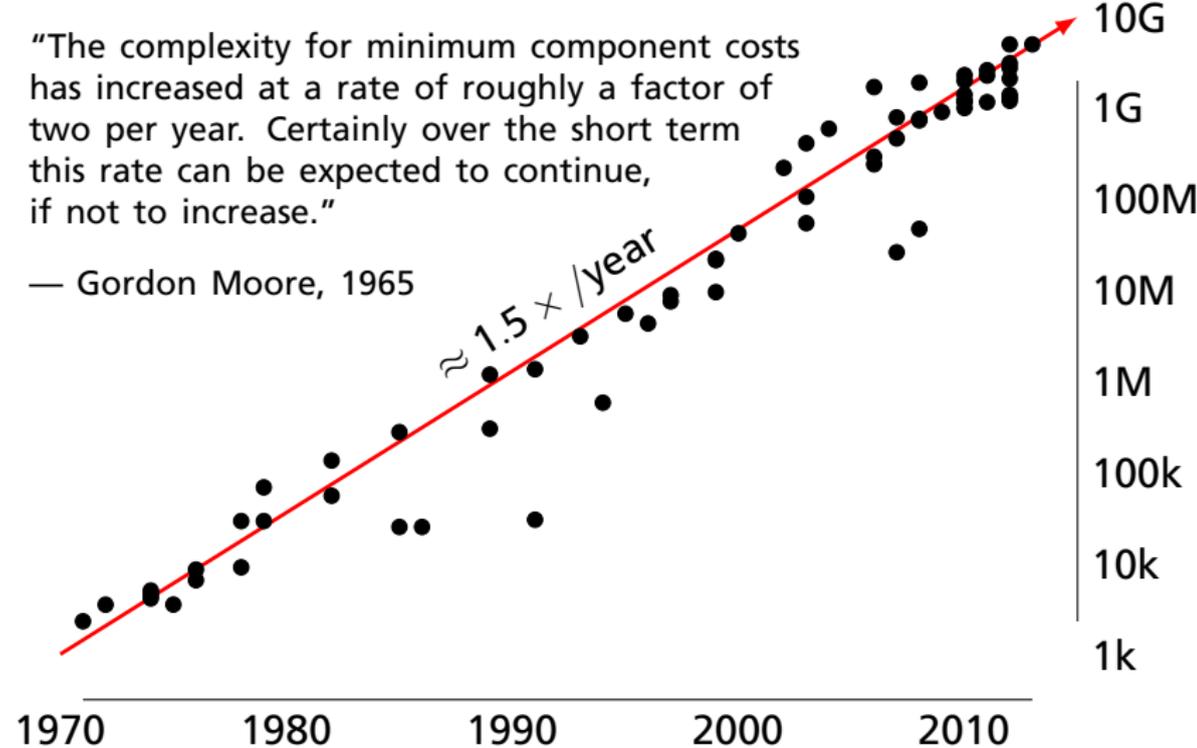
Source: Intel/Wikipedia

$1000 Buys You This Many Cycles per Second
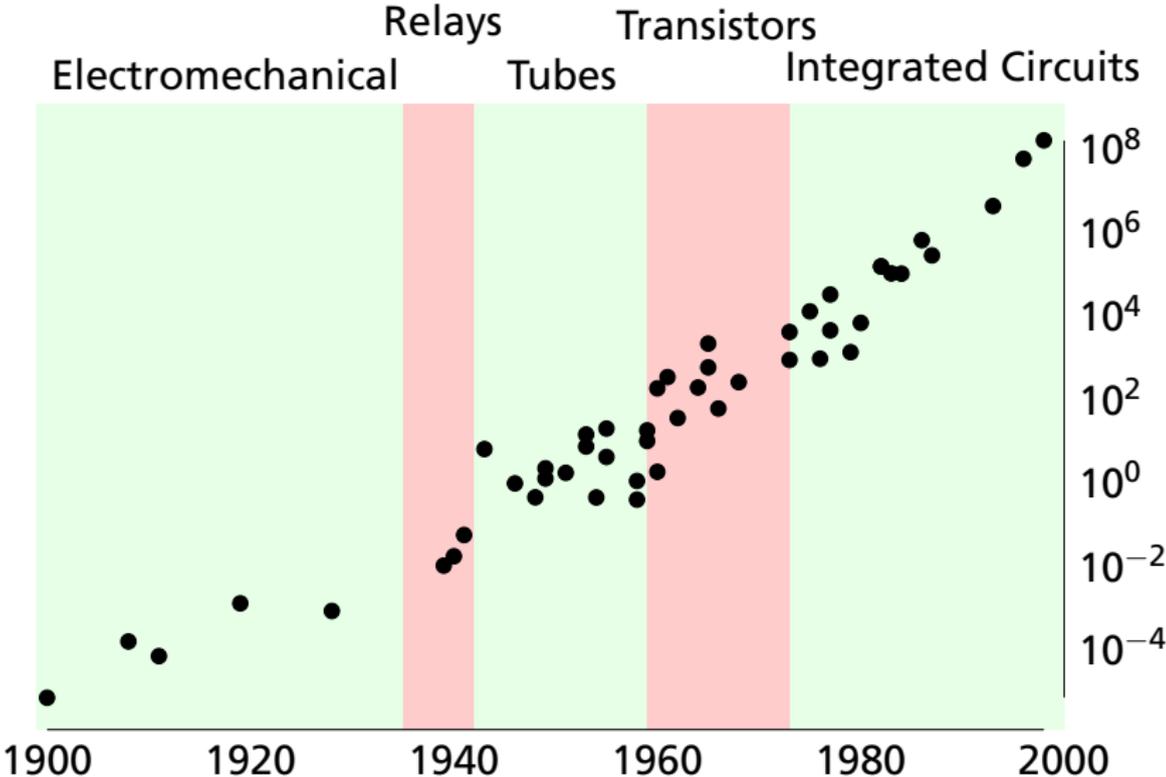
Source: Ray Kurzweil, *The Age of Spiritual Machines*

1918 Sears Roebuck Catalog
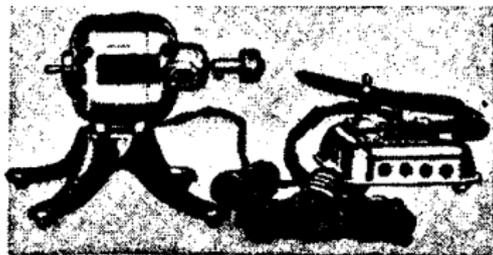
Home Motor.
This motor, as shown above, will operate a sewing machine. Easily attached; makes sewing a pleasure. The many attachments shown on this page may be operated by this motor and help to lighten the burden of the home. Operates on usual city current of 105 to 115 volts. Shipping weight, about 5 pounds.
No. 57P7564 Price, complete, as shown.............. **$8.75**
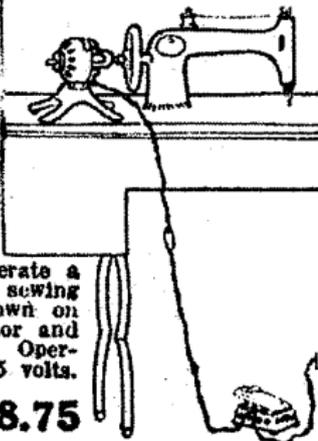
Beater Attachment.
Whips cream and beats eggs, and many other uses will be found for these attachments when used in connection with the Home Motor. Parts include the stand, handle and the beater. Shipping weight, about 14 ounces.
No. 57P7585 Price.......... **$1.30**

Churn and Mixer Attachment.
Used in connection with the Home Motor, makes a small churn and mixer for which you will find many uses. The attachments include the base, supports, mixer, handle and special cover for jar. Shipping weight, about 1¾ pounds.
No. 57P7582 Price.......... **$1.30**

Fan Attachment.
Includes fan and guard which can be quickly attached to Home Motor, and will be a great comfort in hot weather. Shipping weight, about 14 ounces.
No. 57P6215 Price.......... **$1.30**

About $100 in today's dollars.
From Donald Norman, *The Invisible Computer*, 1998.

What Percentage of Time Do You Spend...

	0%	5%	10%	15%	20%	25%
Developing Specifications						
Conceptual Design						
Detailed Design						
Simulation						
Testing/Debugging						
Prototyping						
Sending to production						
Documentation/meetings						
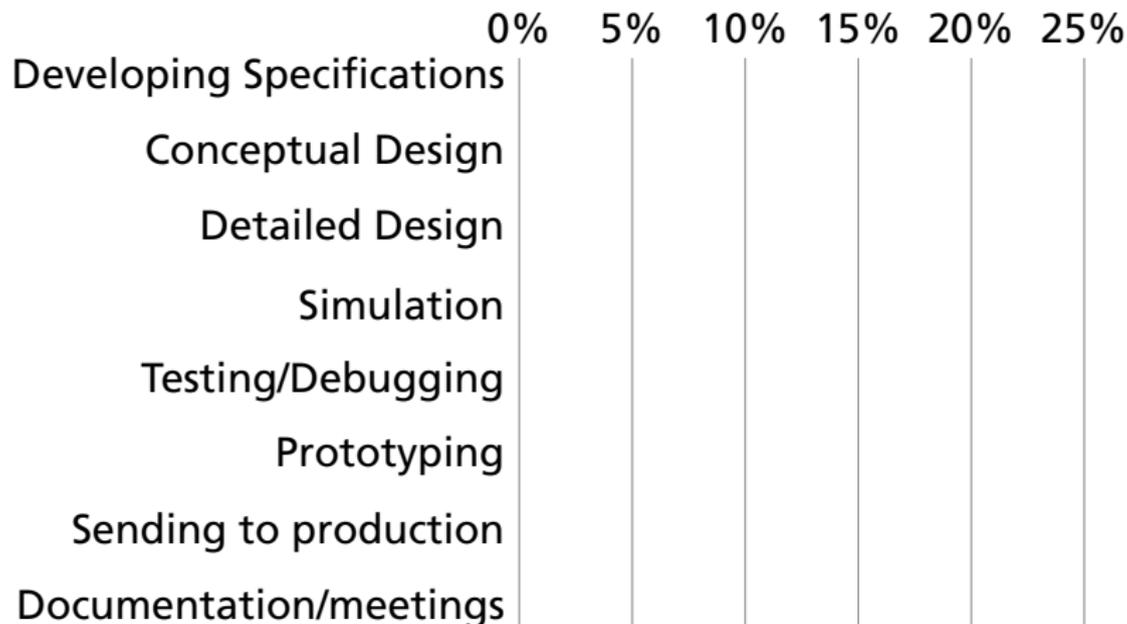
What Percentage of Time Do You Spend...
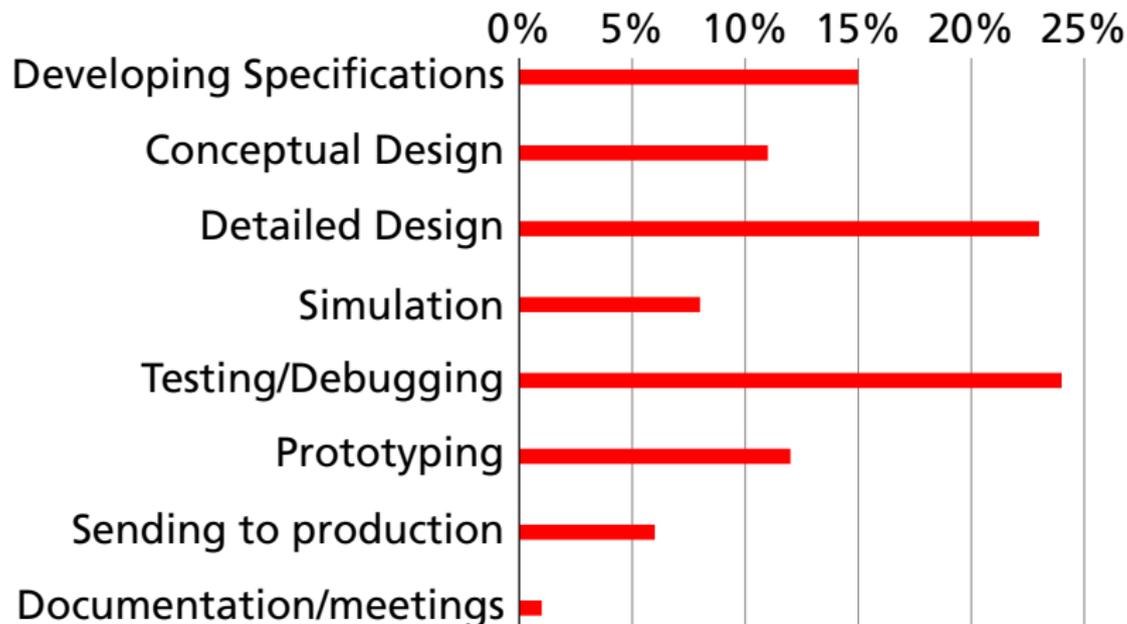
Source: 2009 Embedded Market Study

Does Your Current Project Contain FPGAs?

Does Your Current Project Contain FPGAs?

45%   Yes

55%   No

Source: 2009 Embedded Market Study

Why Won't Your *Next* Project Use FPGAs?

	0%	15%	30%	45%	60%	75%
Don't need them						
Too expensive						
Too power-hungry						
Hard to use						
Too slow						
Too small						
Unreliable						
Don't Know						
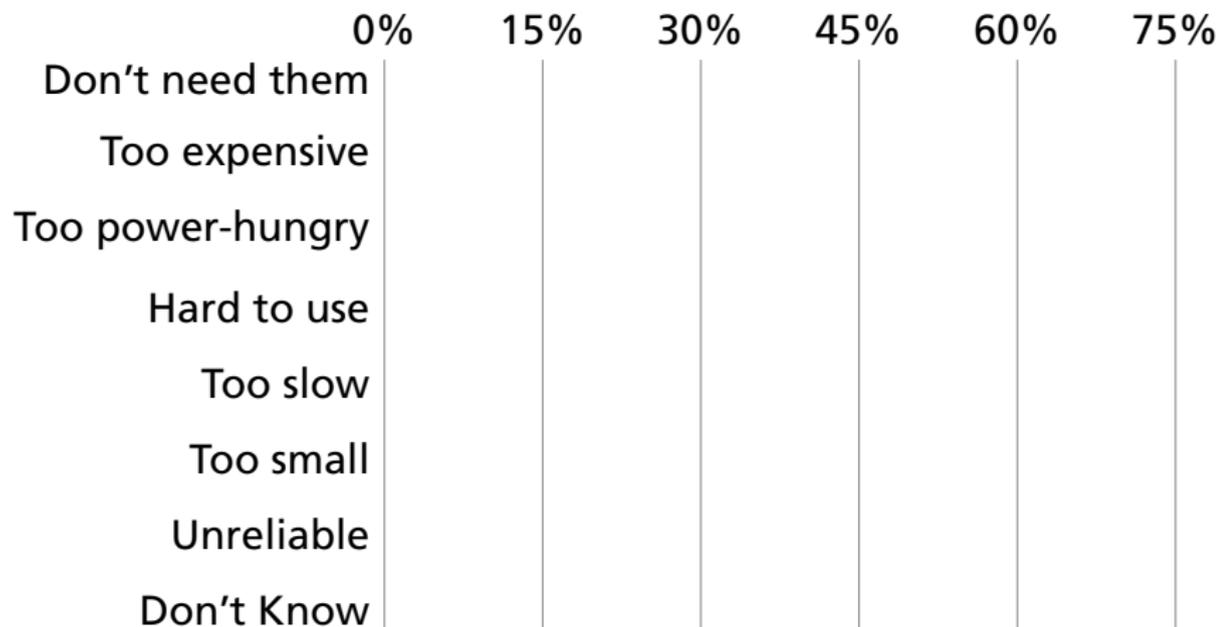
Source: 2009 Embedded Market Study

Why Won't Your *Next* Project Use FPGAs?
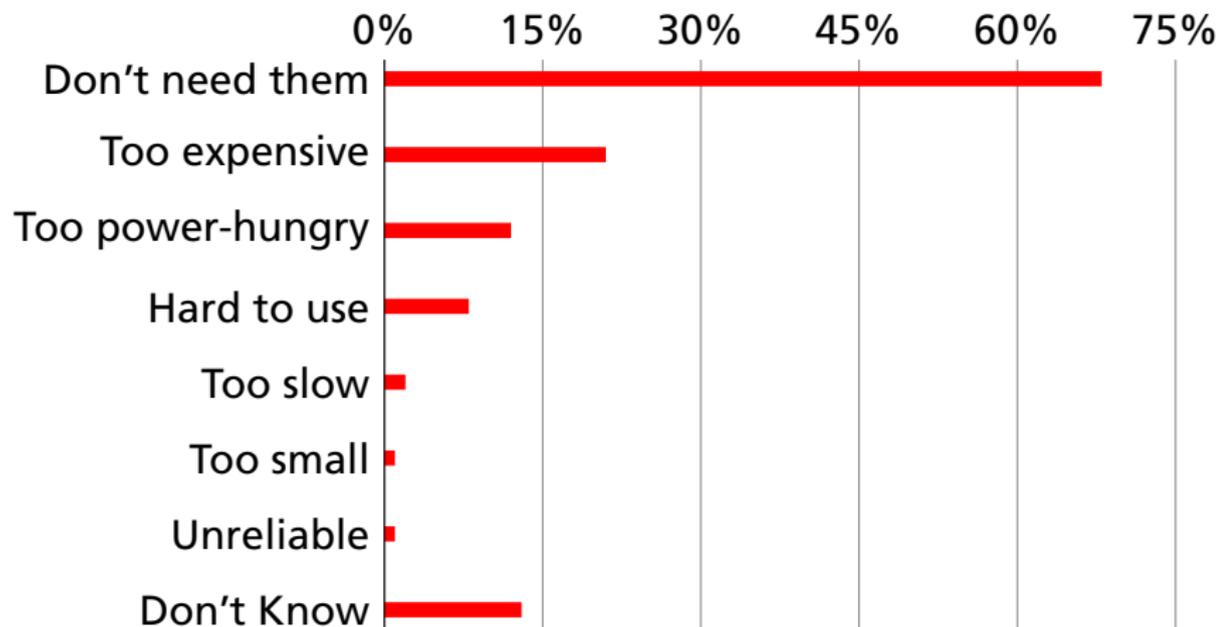
Source: 2009 Embedded Market Study

Your Nemesis: The DE1-SoC Board

Legend:
- FPGA
- HPS
- Systen

Top labels (left to right):
- Mic In
- Line In
- Line Out
- Video-In
- VGA 24-bit DAC
- VGA Out
- HPS Gigabit Ethernet
- HPS USB Host
- UART-to-USB

Left labels (top to bottom):
- JTAG Header
- Audio Codec
- Video Decoder
- PS2
- USB-Blaster II
- Power DC Jack
- Power ON/OFF
- 64MB SDRAM
- ADC
- ADC Header
- 7-Segment Display
- LED x10

Right labels (top to bottom):
- USB HUB
- UART-to-USB Controller
- Micro SD Card
- USB PHY
- Ethernet PHY
- 2x20 GPIO x2
- 1GB DDR3 SDRAM
- Altera 28-nm Cyclone V FPGA with ARM Cortex-A9
- Accelerometer
- 2x7 LTC Expansion Header
- HPS User LED
- IR-out
- IR-in

Bottom labels (left to right):
- Switch x10
- Button x4
- WARM_RST
- HPS_RST
- HPS User Button

USB Blaster II

MAX II
EPM570

25MHz Clock Input
(Clock Generator x1)

Normal Type-B

JTAG

x2

PS/2   x4

Micro
SD Card

x6

SDRAM x16 64 MB   x39

RGMII
x16

TSE
PHY

Ethernet

40 pin GPIO   x36

40 pin GPIO   x36

USB
PHY

USB
Hub

USB Host
Normal Type-A

x13

Video DAC   x29

VGA (8 bit)

Cyclone V
SoC

5CSEMA5F31C6N

Video-In

Video
Decoder

x12

DDR3
SDRAM x32 1 GB

x72

Mic In
Line Out
Line In

Audio
CODEC

x6

HPS I2C

From HPS

FPGA
I2C
x2

Switch Control

UART
to USB

USB Mini-B

x3

IR RX   x1

IR TX   x1

Accelerometer

x3

Clock(Clock Generator) x4

2x7 LTC Header

x7

ADC   x4

FPGA   HPS

x4   x10   x42   x10   x6   x1   x1   x1   x1

Push Button x4

EPCQ256

HPS
User LED

HPS
RST

HPS
User
Button

WARM
RST

Slide Switch x10

LED x10

7-Segment Display x6

Inside the Cyclone V: Dual ARM processors + FPGA
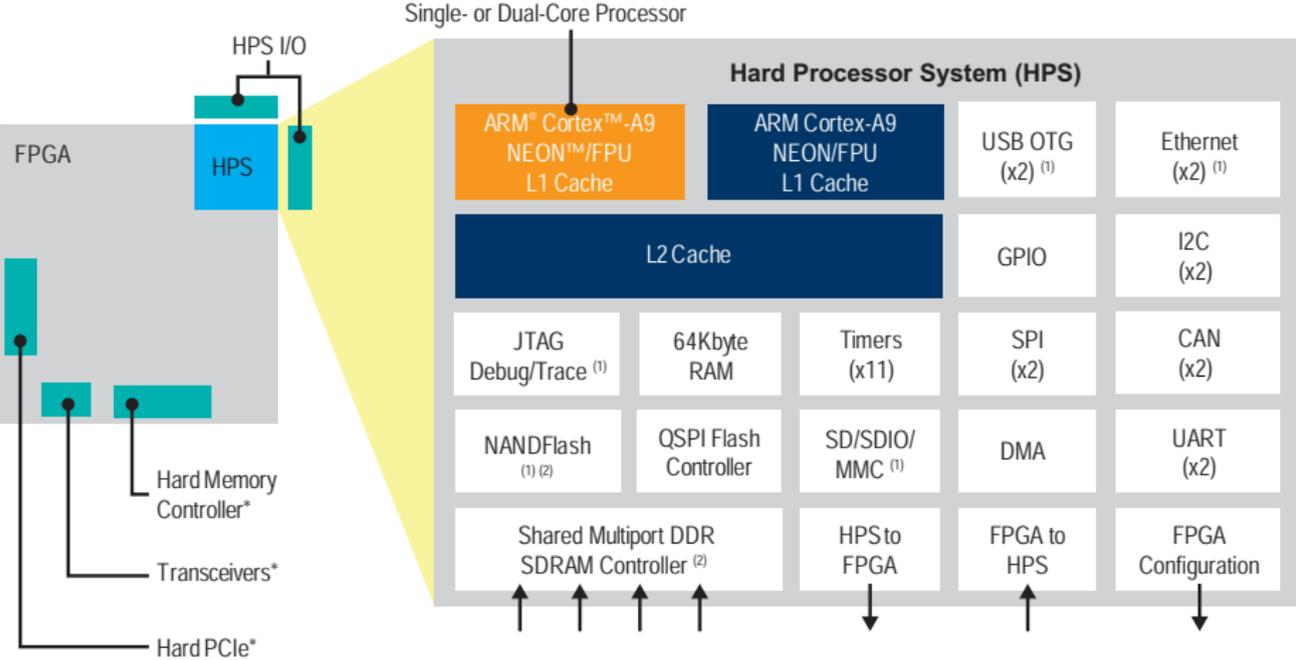
An Example System
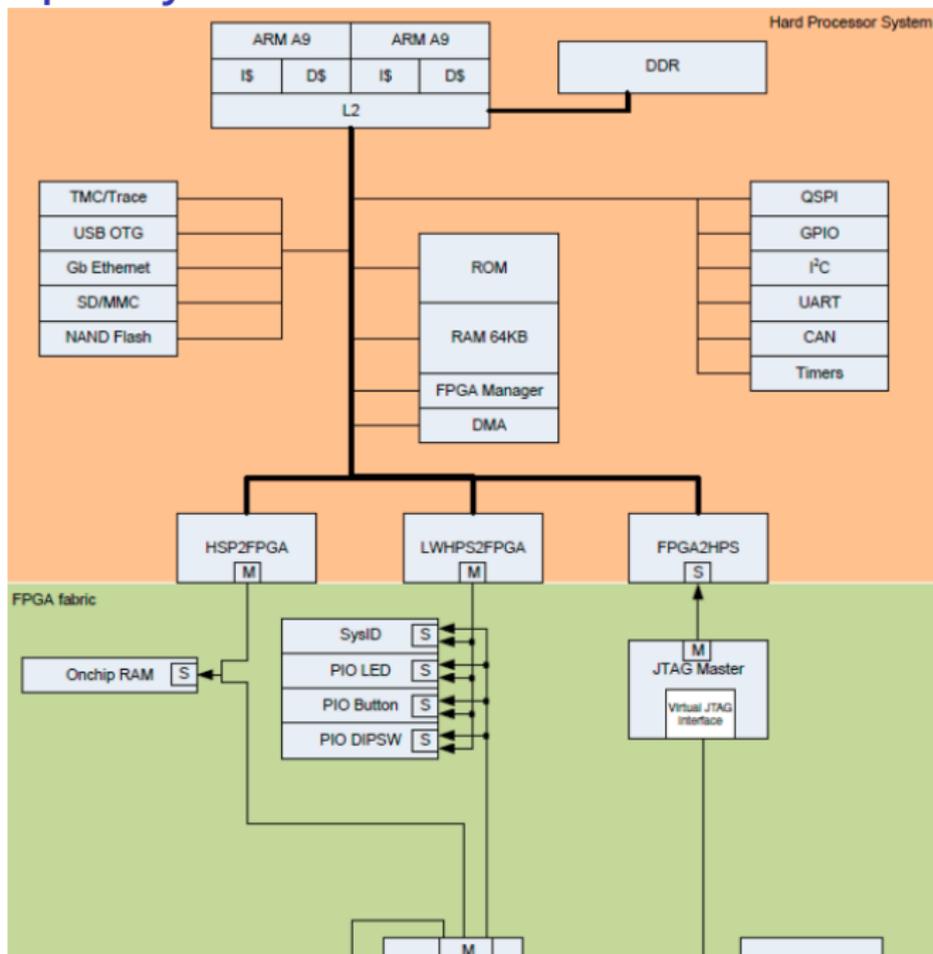
Linux + Custom Hardware

+
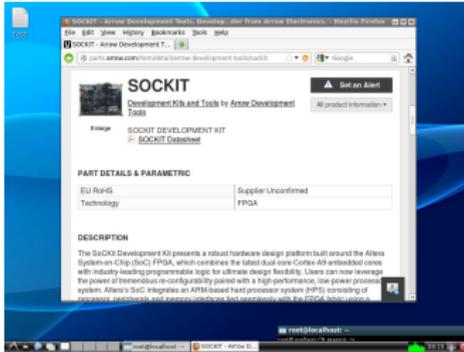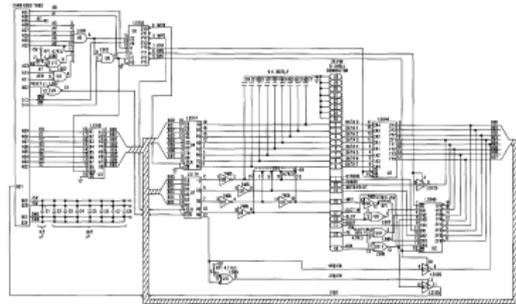
Class Structure

Three Introductory Labs: 2 weeks each

Work in pairs

1. Hardware: Access, modify, and display memory
2. Software: A simple Internet chat client
3. HW + SW: A video bouncing ball

The project: **Design-your-own**

Work in groups of four

Broadly: C + SystemVerilog + peripheral(s)

Broad Project Idea: Video Game

Implement graphics in custom hardware

Put game logic in software

Interface with USB HID (Joystick, etc.)

E.g., Pac-man, 2.5D maze game, tank, worms
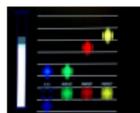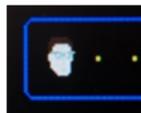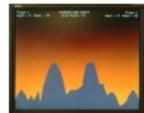
Broad Project Idea: Computational Accelerator
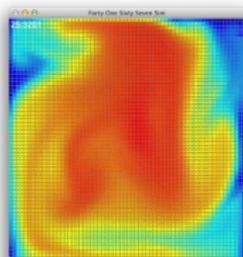
Pick a computationally intensive algorithm

Implement its core in custom hardware

Write software and device drivers that pass data to and from the accelerator

E.g., Smoke simulator, inverse kinematics for robotics, Bitcoin miner

More Ideas

Digital tone control
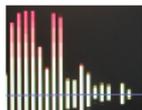
Spectrum analyzer

Internet radio

Speech Synthesizer

MIDI synthesizer

Accelerated JPEG

Game of Life
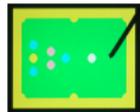
Pool game

Real-time ray tracer

The Three Main Challenges of Embedded Systems

Coping with Real-World Sensor Data
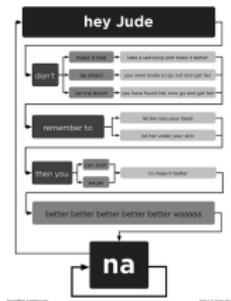

Algorithm Design
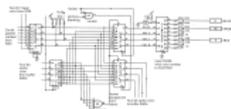
Implementation Details

What Happens When You Press the Switch?
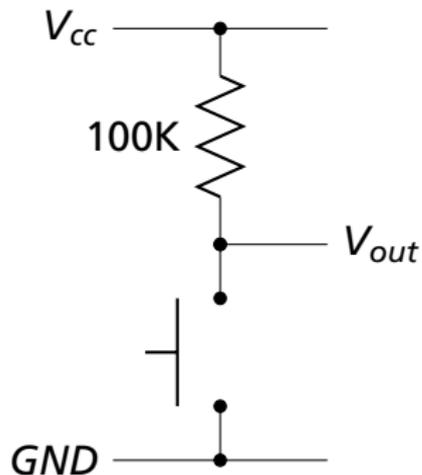
# What Happens When You Press the Switch?
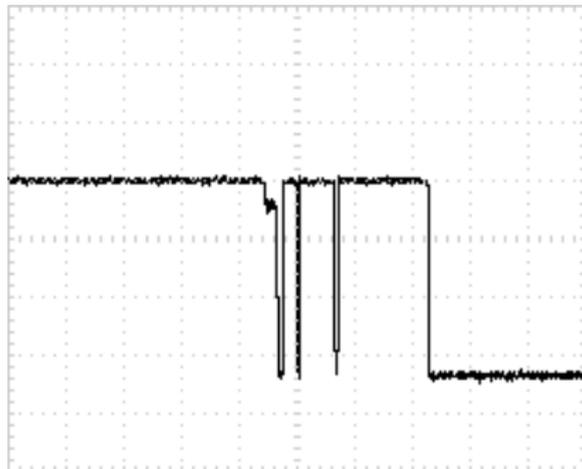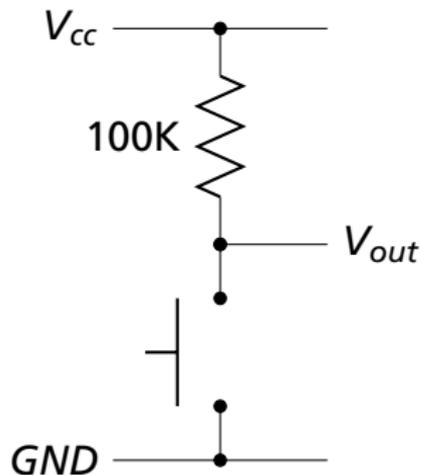
Inside a Pushbutton Switch

Thermoplastic Actuator Button

Thermoplastic Case and Cover

Shorting Bar

Stainless Steel Spring

Terminals

A – View of moveable contact mounted on back side of actuator

Mounting Posts
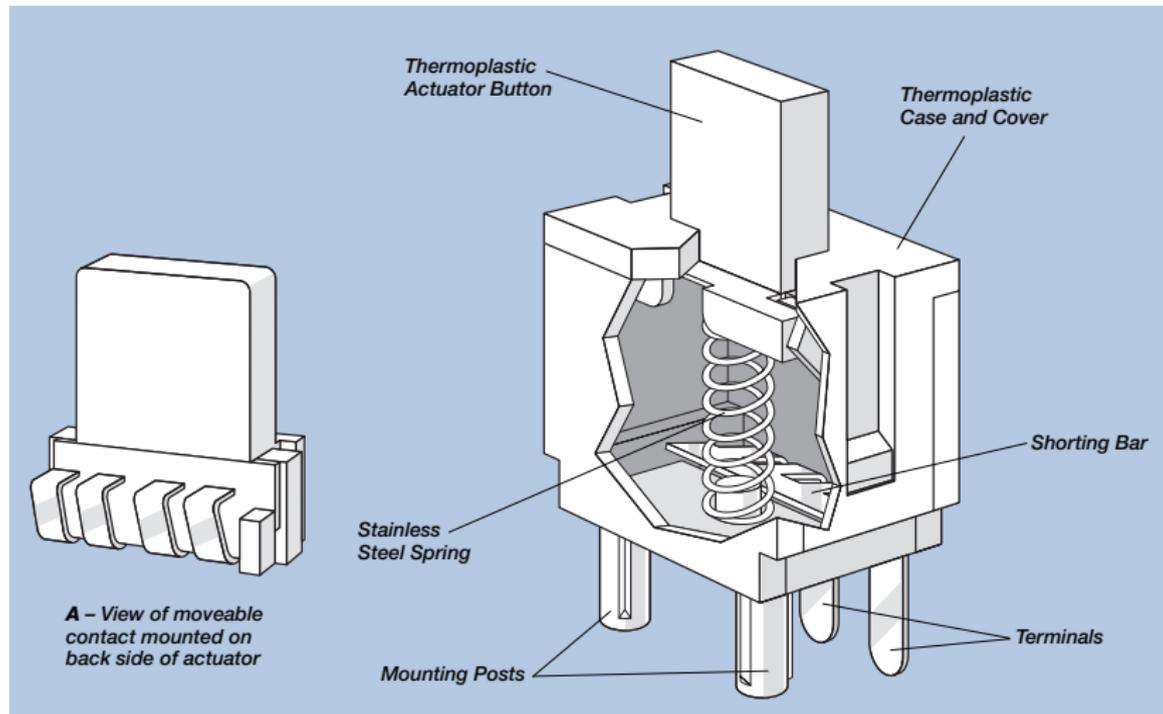
Source: Cherry CS series data sheet

Raw Data from a CCD (zoomed in)
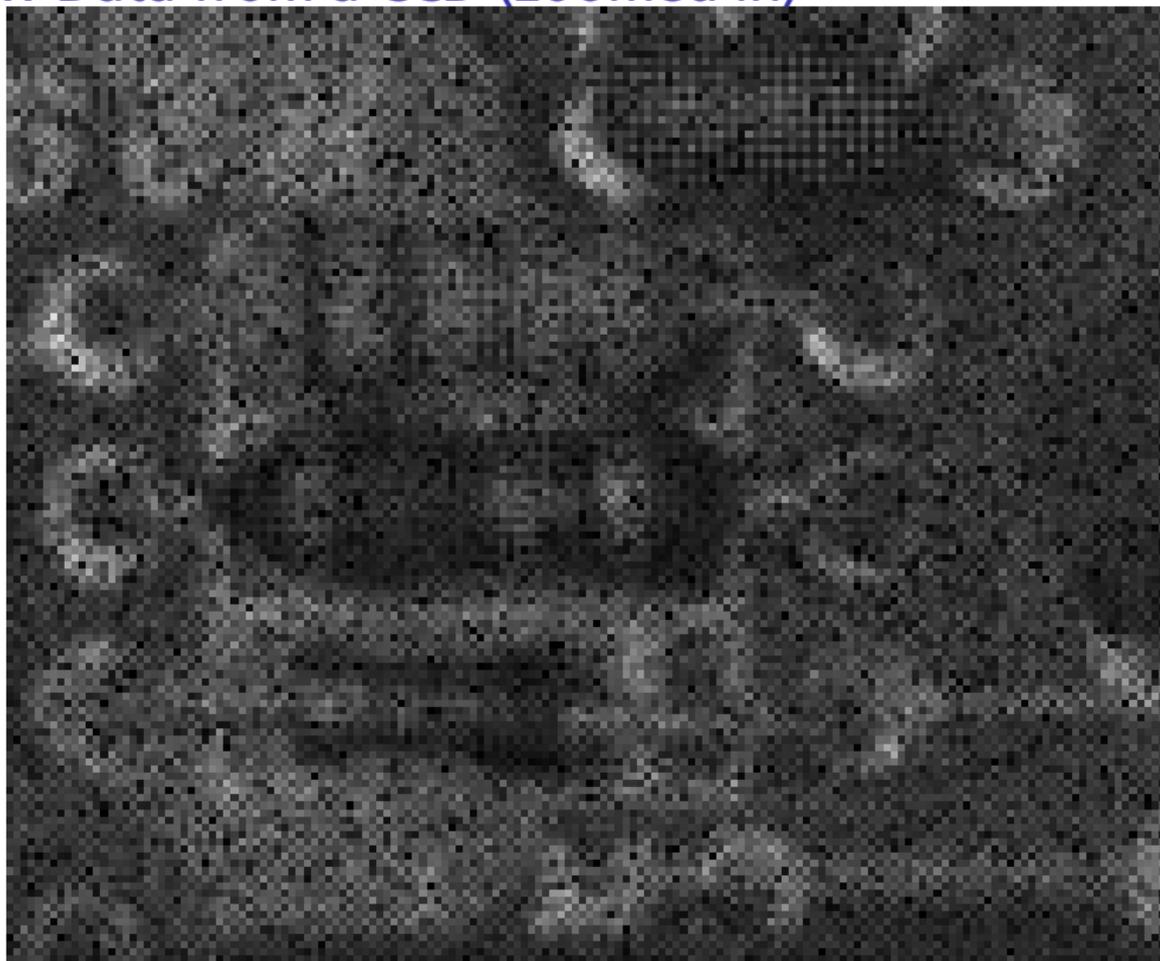
Corrected Image (zoomed in)

Correcting Data from CCDs

Raw − Dark Frame

Flat Field − Bias

=

Color → Temp. → Exposure

Correcting Data from CCDs

Raw − Dark Frame

Flat Field − Bias

=

Color ⟶ Temp. ⟶ Exposure ⟶
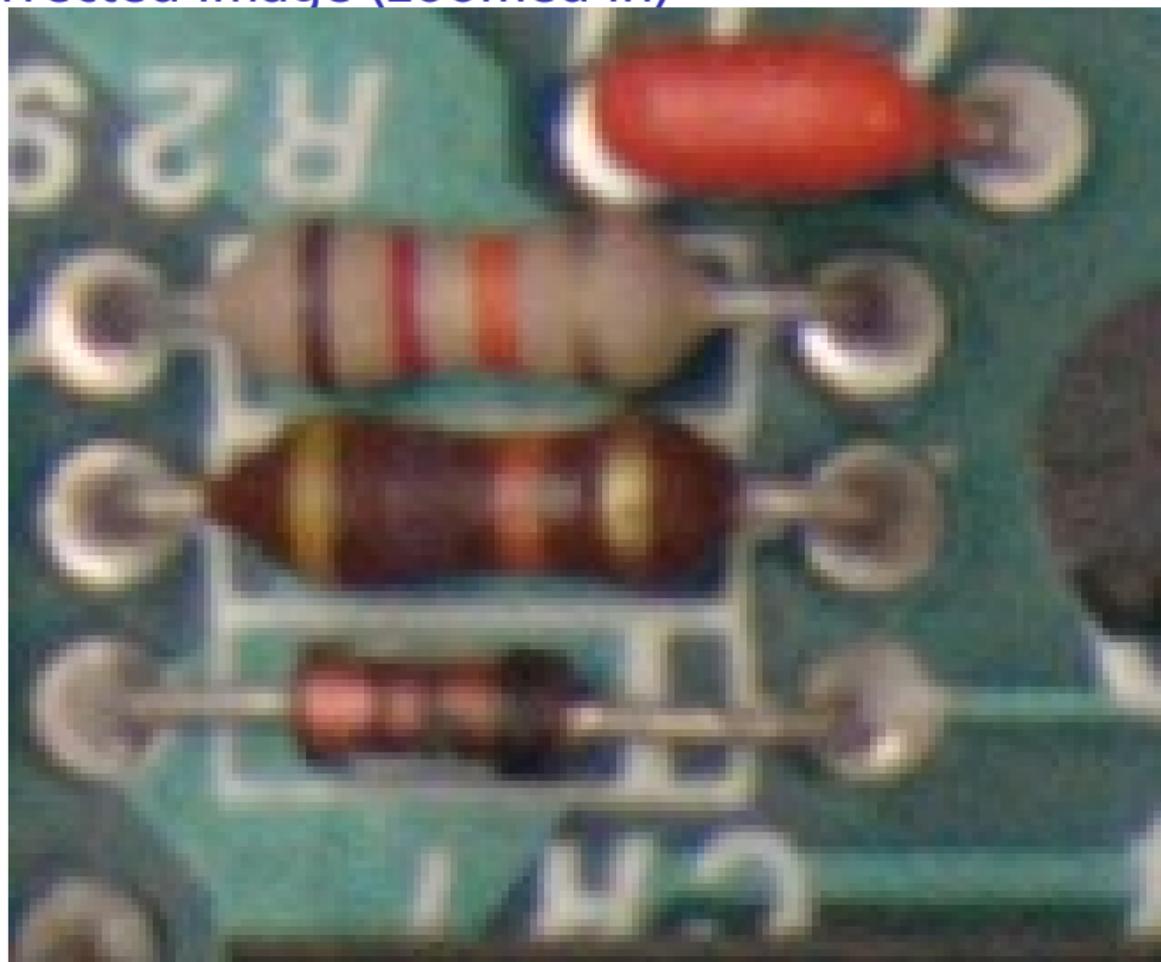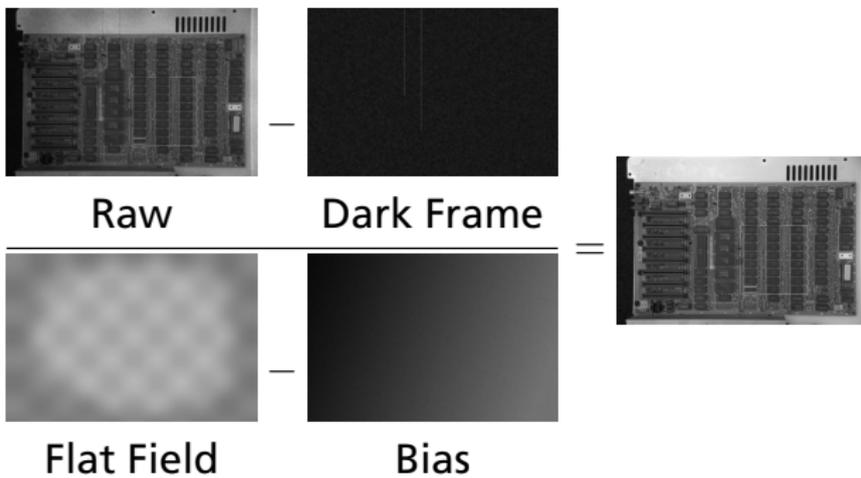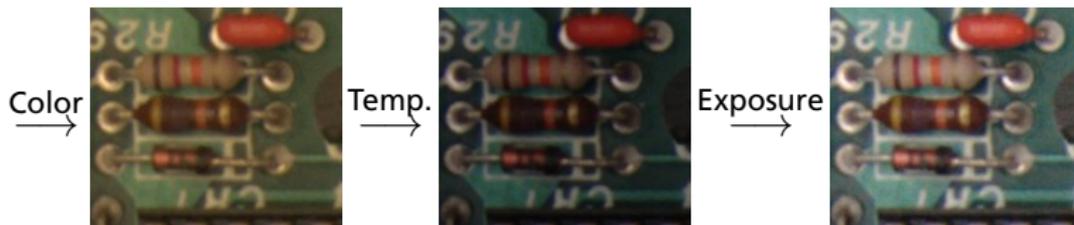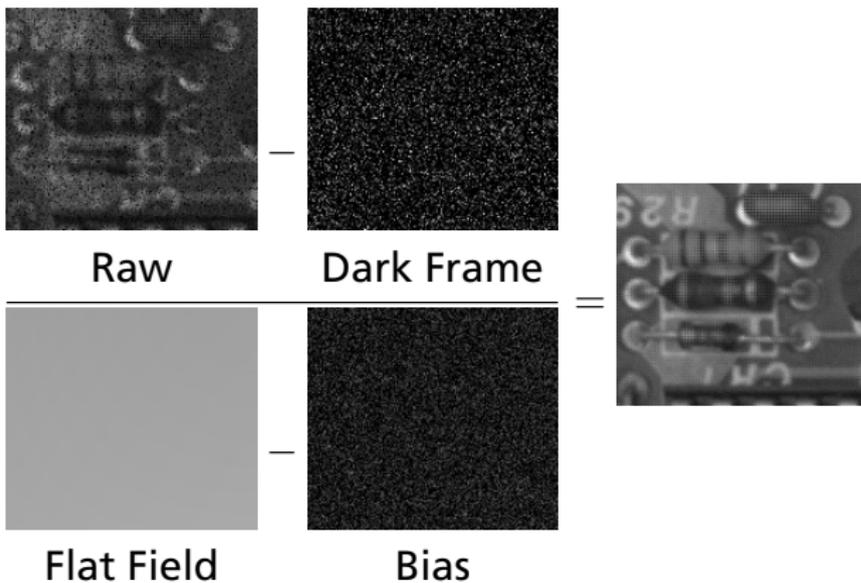
Where Does This Noise Come From?

Nikon D300: 23.6 mm $\times$ 15.8 mm
12.3 megapixel CMOS sensor

Pixels are 5.5 μm on a side

A/D sampling of 12 bits per pixel measures

ISO:	LO	200	400	800	1600	3200
G	7.1	5.5	2.7	1.3	0.65	0.33
B	5.8	4.6	2.3	1.1	0.55	0.27
R	4.7	4.5	2.2	1.1	0.54	0.26

The units: *electrons per ADU* (digital unit).

Emil Martinec, *A comparison of the Nikon D300 and Canon 40D sensors*, 2007.

The Two Big Challenges

- Design the algorithm
  1. Acquire representative input (sensor) data
  2. Conceive of an algorithm
  3. Prototype the algorithm using your favorite language

- Implement the algorithm
  1. Choose a hardware/software partition based on performance and resource constraints
  2. Develop software and hardware architectures
  3. Define interface between software and hardware
  4. Implement the hardware and software
  5. Test, test, test...